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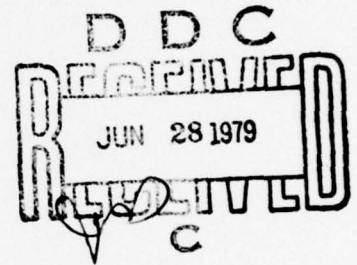
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RESEARCH AND DEVELOPMENT TECHNICAL REPORT
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PREDICTION OF TRANSIONOSPHERIC SIGNAL TIME DELAYS AT
WIDELY SEPARATED LOCATIONS USING CORRELATIVE TECHNIQUES



H. Soicher
COMMUNICATIONS SYSTEMS CENTER ✓

May 1979

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periods during the quiet phase of the solar cycle.

Average regression lines obtained by the analysis were then used to try to determine TEC at Richmond, assuming the availability of TEC in Fort Monmouth, and at Anchorage, assuming the availability of TEC at Richmond. In most cases, the ~~predicted~~ TEC was within one standard deviation of actual observed data for the former case, and within two standard deviations for the latter case.

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PREDICTION OF TRANSIONOSPHERIC SIGNAL TIME DELAYS AT
WIDELY SEPARATED LOCATIONS USING CORRELATIVE TECHNIQUES

INTRODUCTION

The effects of ionization along the satellite-to-ground signal-ray-path on the propagation time of such a signal was previously discussed. (1) The excess time delay introduced by the ionization is directly proportional to the total electron content (TEC) along the signal path. In view of the stringent accuracy requirement of modern satellite-navigation and radar systems, the excess time delay must be compensated for either by real time measurements or through empirical modeling techniques. The former requires that the user possess dual frequency reception capabilities, while the latter (which utilizes a single frequency) depends on how well TEC and its temporal and spatial variability can be modeled and/or predicted. For improved accuracy, the forecasting techniques should be supported by periodic updating of data (preferably in real time) at specified locations. The question arises as to the extent of the geographic area, surrounding a station having real-time TEC-determination capabilities, within which TEC values could be interpolated with acceptable accuracy. In other words, could TEC be determined at Location A if a real-time measurement was taken at a different location, B, and what would be the geographic constraints of A and B?

To this end, a specific investigation designed to determine the correlation (based on linear regression analysis) between TEC values at Fort Monmouth, NJ (40.18°N, 74.06°W) and at Richmond, Florida (25.60°N, 80.40°W) (2), and between TEC values at Richmond, Florida and Anchorage, Alaska (61.04°N, 149.75°W) (3) was undertaken. Beacon transmissions from geostationary satellites were used to determine the TEC at the stations by means of the Faraday rotation technique.

The subionospheric points for the Richmond-Fort Monmouth stations (i.e., the geographic locations where the ray paths to the ATS-6 (located at 94°W) intersect a "mean" altitude of 420 Km) were 36.5°N, 76.6°W, and 23.6°N, 81.6°W, respectively. Thus, the "representative" TEC for the two stations was separated by $\sim 13^\circ$ in latitude and by $\sim 5^\circ$ in longitude corresponding to a 20-minute difference in local time). The subionospheric points for the Richmond-Anchorage monitoring the SMSI (located at 105°W),

- 1 H. Soicher, "Ionospheric and Plasmaspheric Effects in Satellite Navigation Systems", IEEE Trans. Antennas & Propagation, Vol AP-25, No. 5, Sep 77.
- 2 H. Soicher, "Spatial Correlation of Transionospheric Signal-Time-Delay", IEEE Trans, Antennas & Propagation, Vol AP-26, No. 2, March 1978.
- 3 H. Soicher, "Correlation of Satellite Signal Time Delays at Widely Separated Locations", submitted to IEEE Trans. Antennas & Propagation.

and the ATS-6 (located at 140°W), respectively, were 22.5°N , 82.7°W and 54.3°N , 147.3°W respectively. The "representative" TEC was separated by $\sim 31.8^{\circ}$ in latitude and $\sim 63.8^{\circ}$ in longitude (corresponding to a 4 hr 15 minute difference in local time).

The correlation data indicated that TEC, or equivalently, ionospheric signal time-delays, are highly correlatable at the two sets of locations. When daily data sets were compared at approximately the same local time the correlation coefficients were, in general, $\gtrsim 0.9$ for the Fort Monmouth-Richmond locales, and $\gtrsim 0.7$ for the Richmond-Anchorage locales.

The next phase of the investigation was the effort to determine whether it is possible to accurately predict TEC at one locale from TEC at the other, using average regression lines obtained for the corresponding data sets. The technique employed was as follows: Average monthly regression lines were computed. In one case, average slopes as well as average intercepts of the regression lines at monthly intervals were computed. In a second case, average slopes were computed while the intercepts were forced to pass through a common data point for the two sets at a specific predawn time for each day. Having determined the average regression lines, TEC at one locale was calculated for a given TEC at the corresponding other locale. The deviation (D_i) of the calculated TEC from its actual value at a particular time is then determined. This deviation, D_i is then divided by σ_i , the monthly TEC standard deviation value at the same time. The average absolute value of this ratio, i.e., $\frac{|D|}{\sigma}$ was then computed for each day.

The results for the Fort Monmouth-Richmond data sets (i.e., predicting TEC at Richmond from TEC at Fort Monmouth) using average slopes and intercepts of the monthly regression lines are shown in Fig. 1. The results using average slopes and forcing the average regression lines to pass through common points at 0200 UT, are shown in Fig. 2. Also shown in Figs. 1 and 2 is the number of data pairs available for the analysis for each day (data is available at 15-minute intervals; ninety-six data points signify a full day's data availability. Data is sometimes missing, due to turn-off of the satellite's beacons). The results using average slopes and intercepts of the monthly regression lines, but for the time period 1500-2100 UT, when the maximum diurnal TEC values occur are shown in Fig. 3. Similarly the results using average slopes and forcing the average regression lines to pass through common points at 0200 UT are shown in Fig. 4.

The results for the Richmond-Anchorage data sets (i.e., predicting TEC at Anchorage from TEC at Richmond for the same local time) using average slopes and intercepts of the monthly regression lines are shown in Fig. 5. The results using average slopes and forcing the average regression lines to pass through common points (at 0200 UT at Richmond and the correspondingly-shifted time at Anchorage), are shown in Fig. 6. The results using average slopes and intercepts of the monthly regression lines, but for the time period 1500-2100 UT (for Richmond and the correspondingly-shifted time for Anchorage), when the maximum diurnal TEC values occur are shown in Fig. 7. Similarly, the results using average slopes and forcing the average regression lines to pass through common points at 0200 UT (Richmond time) are shown in Fig. 8.

DISCUSSION

As Fig. 1 indicates, the daily average of the ratios $\frac{D}{\sigma} = \frac{1}{N} \sum_{i=1}^N \frac{|D_i|}{\sigma_i}$, $N \leq 96$

for Richmond is, for the most part, smaller than one, i.e., on the average, the deviation of the computed Richmond TEC values from Fort Monmouth TEC values is, in general, within the monthly standard deviation of the Richmond data. The diurnal behavior of the ratio is such that the ratio is higher during the night (when σ is small) than during the day. Some of the high values of this ratio are attributable to ionospheric effects during magnetically active periods, e.g., on September 15 and 18, 1974, large enhancement of TEC were observed in response to magnetic sudden commencements; on March 11, the K_p index ranged from 4^o to 7⁻. The results of the figure also indicate that the ratio appears larger during the equinoctial period (September, March) than during the winter and spring months. This is observed despite the fact that the standard deviation during the equinoctial months was considerably higher than during the other months. The ratio, in general, does not change substantially (as compared to the above case) when the average regression slopes are forced to pass through the actual data points at the two locations at 0200, as may be seen by comparing Figs. 2 and 1. This happens despite the fact that D is smaller during the night (although σ is also small compared to its day values).

As Fig. 5 indicates, the daily average of the ratios $\frac{|D|}{\sigma}$ for Anchorage is for the most part, smaller than two, i.e., on the average,

the deviation of the computed Anchorage TEC values from the corresponding Richmond TEC values, is, in general, within two standard deviations of the Anchorage data. As in the Fort Monmouth-Richmond data sets the diurnal behavior of the ratio is such that the ratio is higher during the night than during the day. In addition, the figure indicates that the ratio is larger on the average in October than in the following two months. This occurs despite the fact that the correlation coefficient was, on the average, higher in October, declined in November and declined further in December (due to changes in TEC diurnal shapes associated with changing separation in sunrise and sunset times at the two locales) (3). As with the Fort-Monmouth-Richmond case, the ratio here does not change substantially (as compared to the above case) when the average regression lines are forced to pass through the actual data points at the two locations at 0200 UT Richmond time (and the correspondingly shifted Anchorage time), as may be seen by comparing Figs. 5 and 6. The disadvantage of using this technique for possible operational application, is, of course, the inavailability of any data points at the locale where the predictions are to be made.

Since total signal time-delays are largest during the day and thus, introduce significant errors in navigation and radar systems, it is

appropriate to examine the ratio D/σ during the time when TEC is diurnally larger, i.e., between 1500 and 2100 UT (Richmond, Fort Monmouth times and corresponding Anchorage time).

For the Fort Monmouth-Richmond case Figs. 3 and 4 indicate that the ratio D/σ , obtained by average regression lines computed by the two techniques for the day period, are substantially lower than the corresponding ratios for the full diurnal periods (Figs. 1 and 2). The fact that the bulk of the data indicates that the ratio falls below 1 is encouraging since both correlation methods yield "predicted" TEC values that fall within the monthly standard deviation of the data during the time period when the presence of TEC poses the source of largest error.

For the Richmond-Anchorage case a similar statement cannot be made. On the average, the ratio is not markedly different for the full time interval and for the time interval for maximum values of TEC.

CONCLUSIONS

The high correlation of signal time delay variation at two sets of locale separations, one widely separated by latitude, and the other widely separated by latitude and longitude (and hence by local time), prompted the examination as to whether time-delay data at one locale may be "predicted" if continuous corresponding data were available at the other locale. The correlation is high, in part, due to the 24 hour periodicity of the data. It is precisely this periodicity, however, that gives the "prediction" technique employed here its accuracy. The variation of the time delay is the highly correlatable quantity, and thus, the whole data set - if available, should be used in the prediction scheme.

Monthly average regression lines were used in the analysis. The slopes of the average monthly regression lines was within $\pm 20\%$ from their average for the whole period. The intercepts of the monthly lines of regression were considerably more scattered.

For the two locales separated mainly in latitude (Fort Monmouth-Richmond) the deviation of the "predicted" data from the observed data was for the most part, within one standard deviation of the monthly data set. For the daytime period, when the error introduced by the time-delay is greatest, the ratio D/σ was even lower. When the average regression line for the entire period considered was calculated (i.e., the average of six monthly averages), the bulk of the "predicted" data was still within one standard deviation of the monthly data set. The ratio is often high during time periods characterized by ionospheric disturbances.

For the two locales widely separated by latitude and longitude (Richmond-Anchorage), the deviation of the "predicted" data from the observed data was, for the most part, within two standard deviations of the monthly data set. When the average regression line for the entire period was used, the bulk of the "predicted" data was still within the two standard deviations of the monthly data sets.

Since the monthly value of the standard deviation is $\sim 25\%$ of the absolute value of the time delay, the method of prediction outlined here appears to have the capability of correcting the time delay due to the ionosphere to within $\sim 25\%$ for stations separated in latitude, and $\sim 50\%$ for stations widely separated in latitude and longitude.

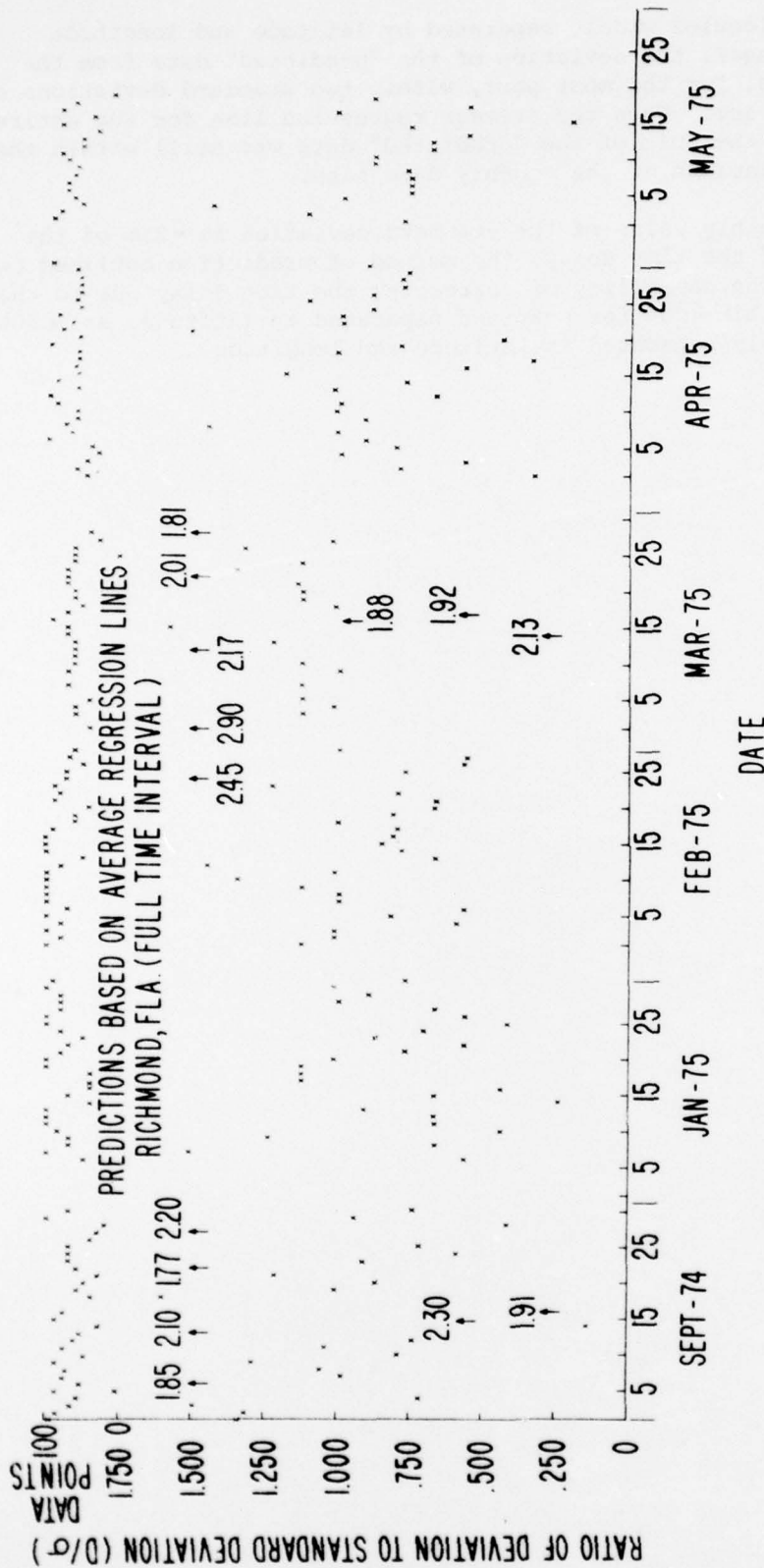


FIGURE 1

The variation of the ratio D/σ for Richmond, Florida, for the time period September 1974, and January 1975-May 1975, calculated for full diurnal periods by average regression lines obtained by Fort Monmouth, NJ-Richmond, Florida data sets. (D is diurnal average of the deviations of the computed TEC values from observed ones; σ is monthly standard deviation of the Richmond data.) The arrows and the corresponding numerical values are for those values of the ratio which exceed the scale of the Figure. Also indicated in the upper portion of the Figure are the number of TEC data pairs at 15-minute intervals used in the analysis.

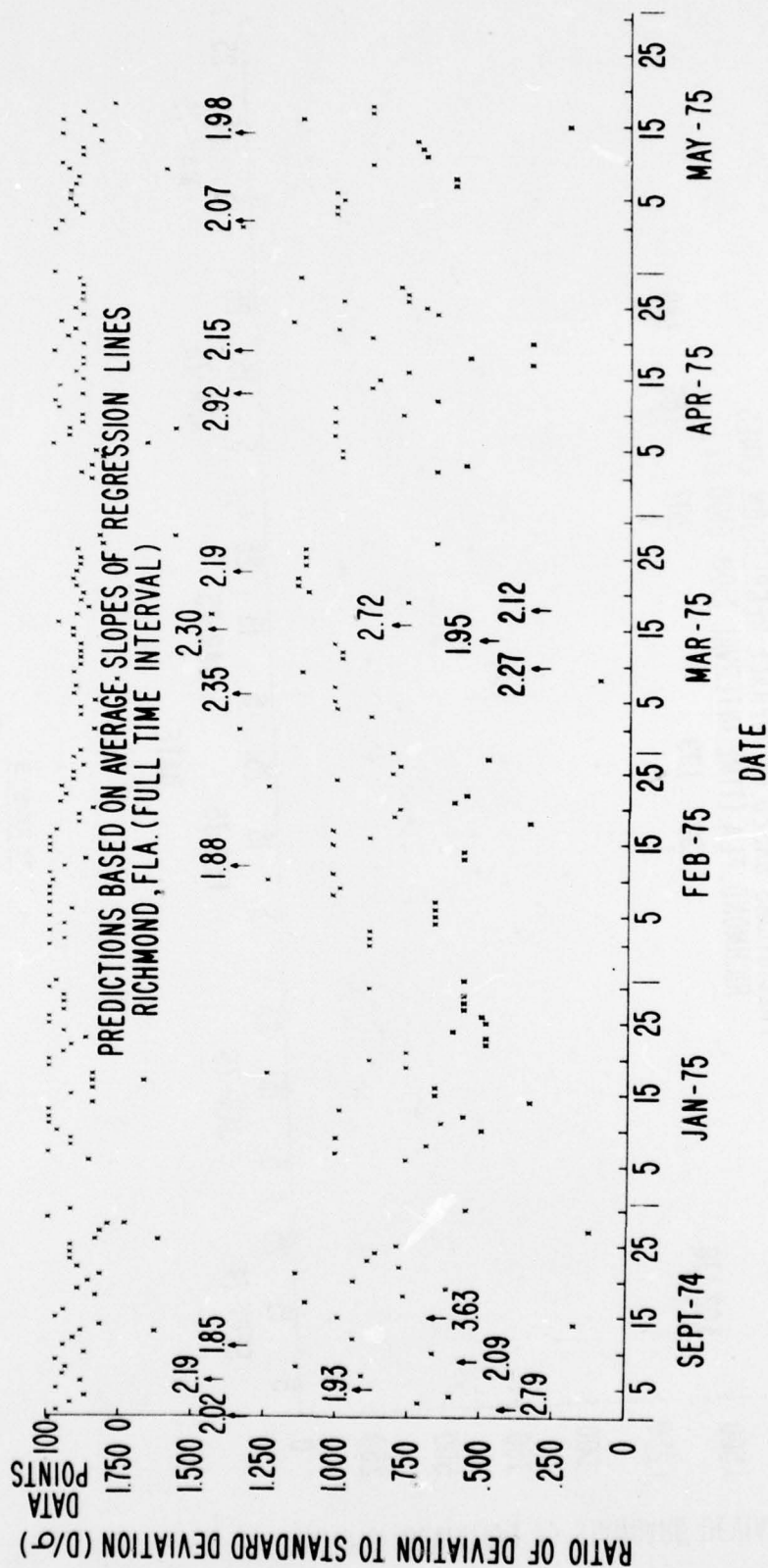


FIGURE 2

Same as Figure 1, except the average calculated regression slopes are forced to pass through common TEC values at 0200 UT.

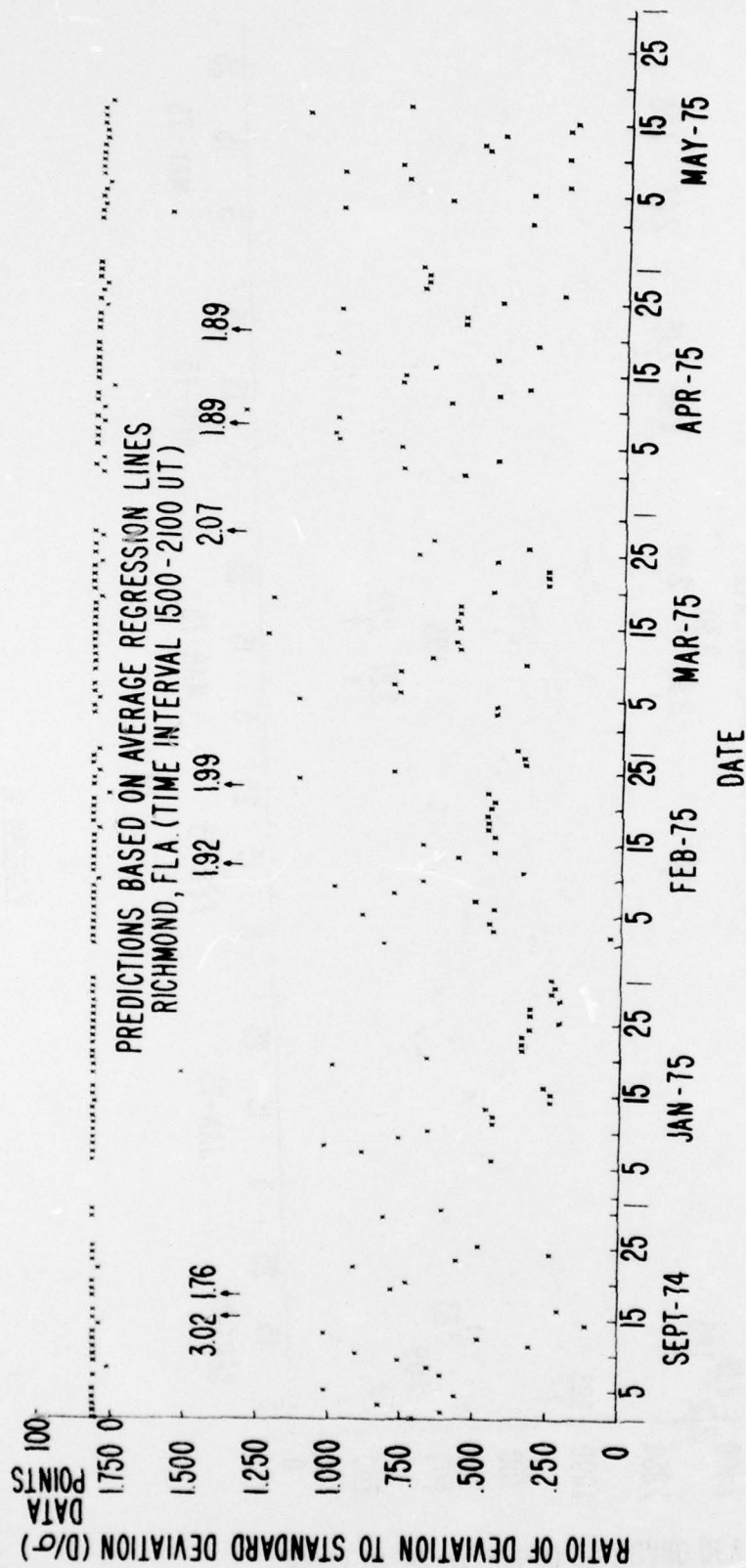


FIGURE 3

Same as Figure 1, except that the ratios are computed only for the time period 1500-2100 UT

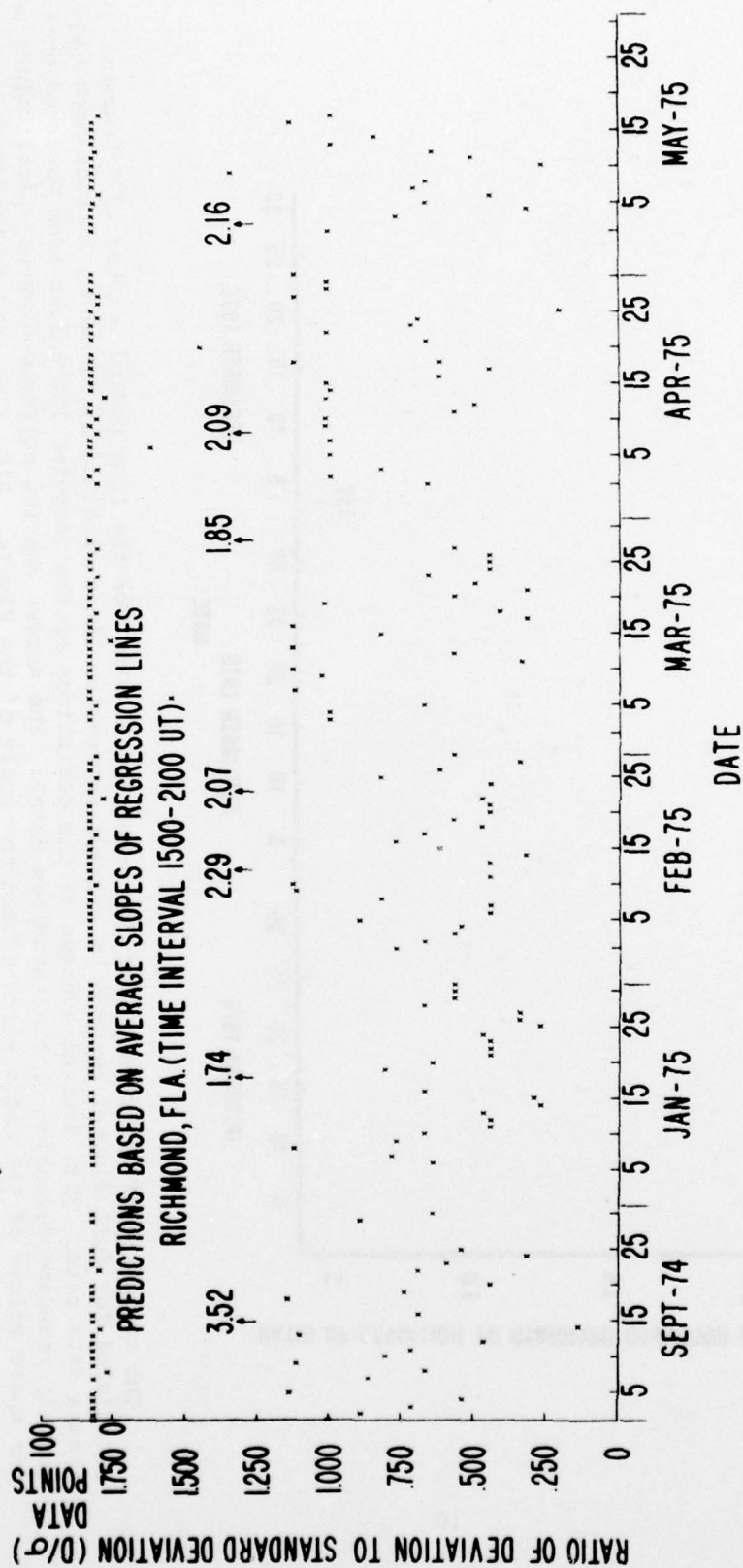
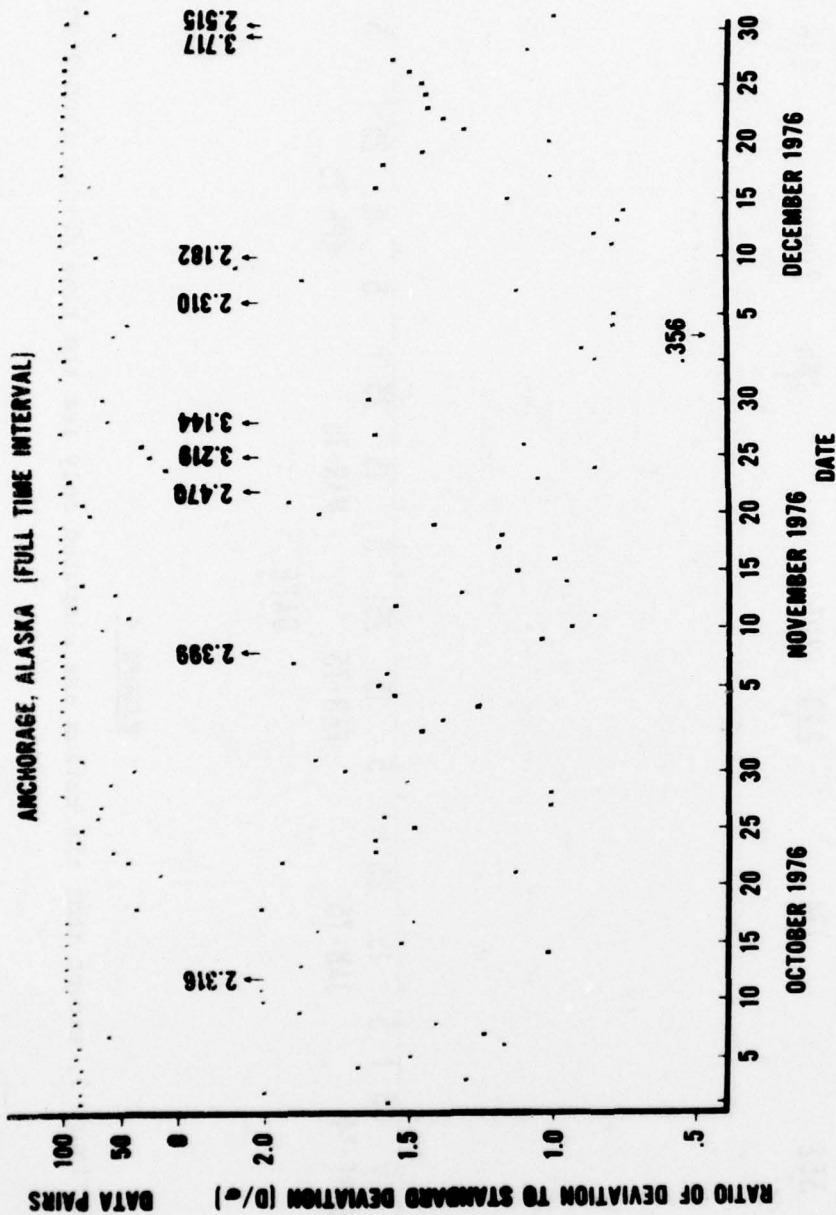


FIGURE 4

Same as Figure 2, except that the ratios are computed only for the time period 1500-2100 UT

PREDICTIONS BASED ON AVERAGE REGRESSION LINES

ANCHORAGE, ALASKA (FULL TIME INTERVAL)



The variation of the ratio D/σ for Anchorage, Alaska, for the time period October 1976-December 1976, calculated for full diurnal periods by average regression lines obtained by Richmond, Florida-Anchorage, Alaska data sets. (L_r diurnal average of the deviations of the computed TEC values from observed ones; monthly standard deviation of the Anchorage data). The arrows and the corresponding numerical values are for these values of the ratio which exceed the scale of the Figure. Also indicated in the upper portion of the Figure are the number of TEC data pairs at 15 minute intervals used in the analysis.

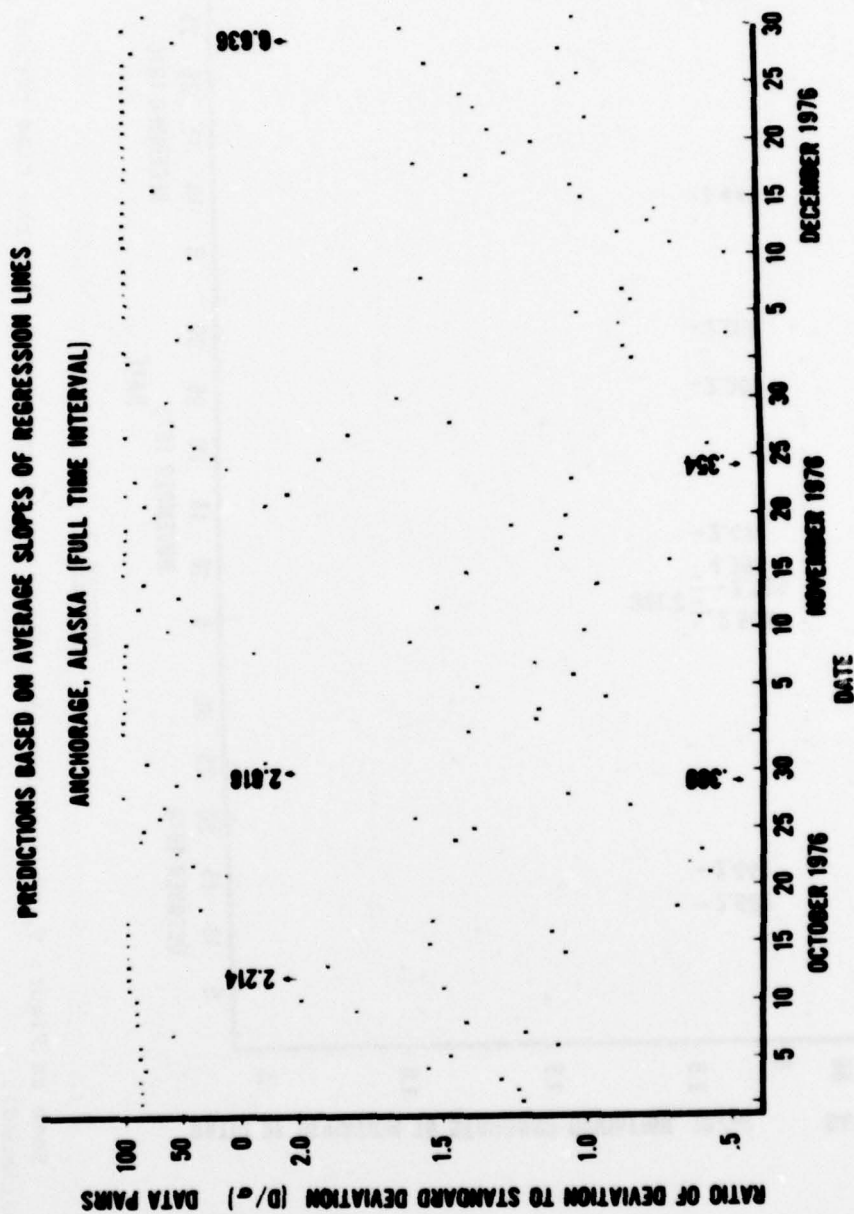


FIGURE 6

Same as Figure 5, except the average calculated regression slopes are forced to pass through common TEC values at 0200 UT (Richmond).

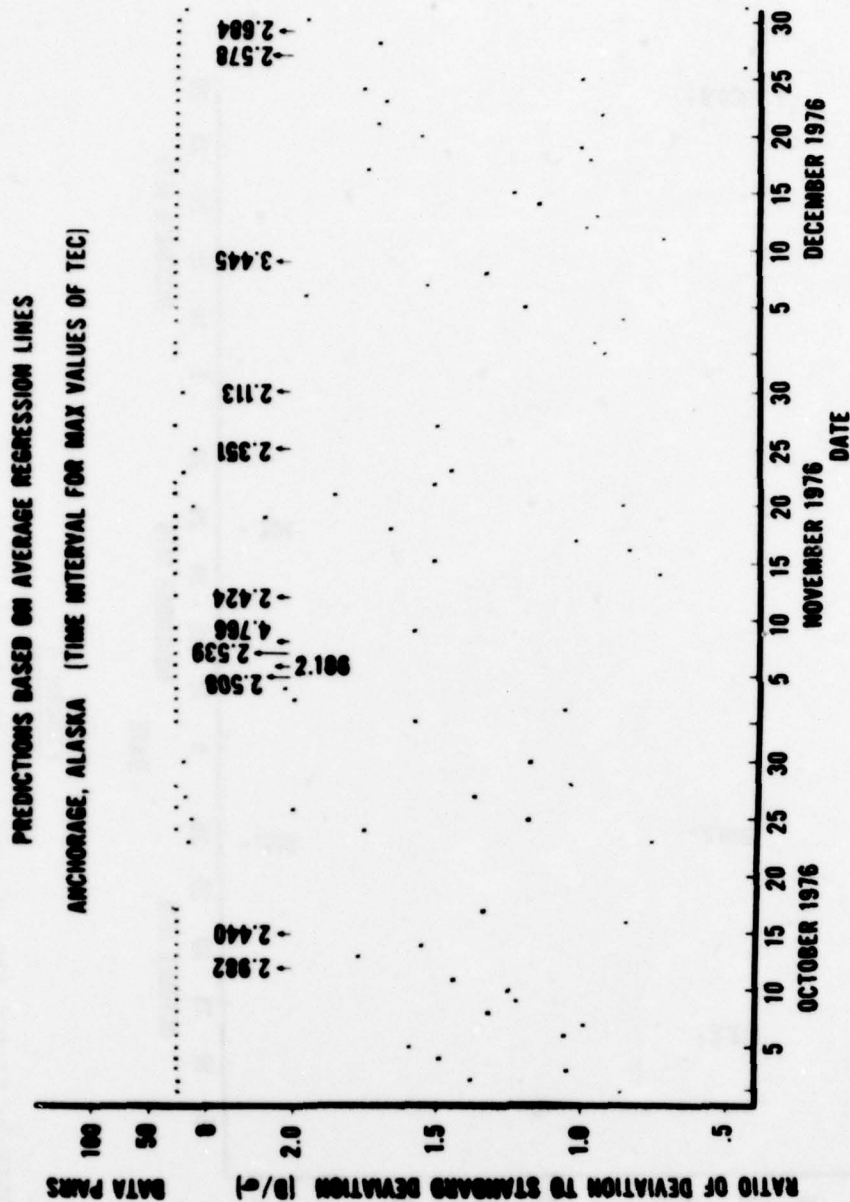


FIGURE 7

Same as Figure 5, except that the ratios are computed only for the time period 1500-2100 UT (Richmond).

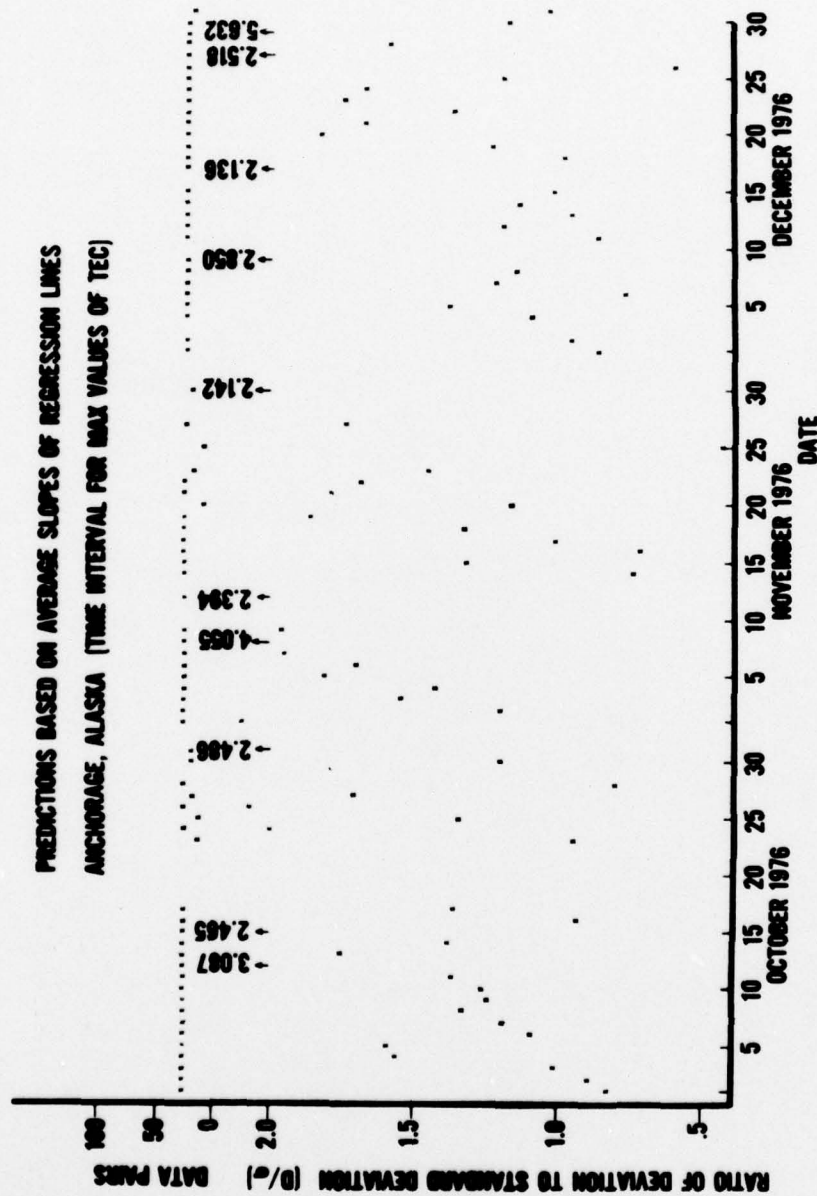


FIGURE 8

Same as Figure 6, except that the ratios are computed only for the time period 1500-2100 UT (Richmond).